Global Estimates of 3D Effects and the Sensitivity of GCMs to Subgrid-Scale Cloud Structure

Howard W. Barker   *Jason N. S. Cole*

Meteorological Service of Canada

- a global estimate of 3D RT effects
  - 2D MMF data + SW and LW MC algorithms
- RT and climate modelling
  - how advanced are we?
  - prospects for 3D RT
  - examples of McICA noise impacts

Cloud Physics and Severe Weather Research Division
Environment Canada

A global estimate of 3D RT effects

- Cole, Barker, O'Hirok, Clothiaux, Khairoutdinov, and Randall, 2005: Atmospheric Radiative Transfer Through Global Arrays of 2D Clouds. In press: *Geophys. Res. Lett.*

- MMF-GCM:

  - 2D CSRM in each GCM column

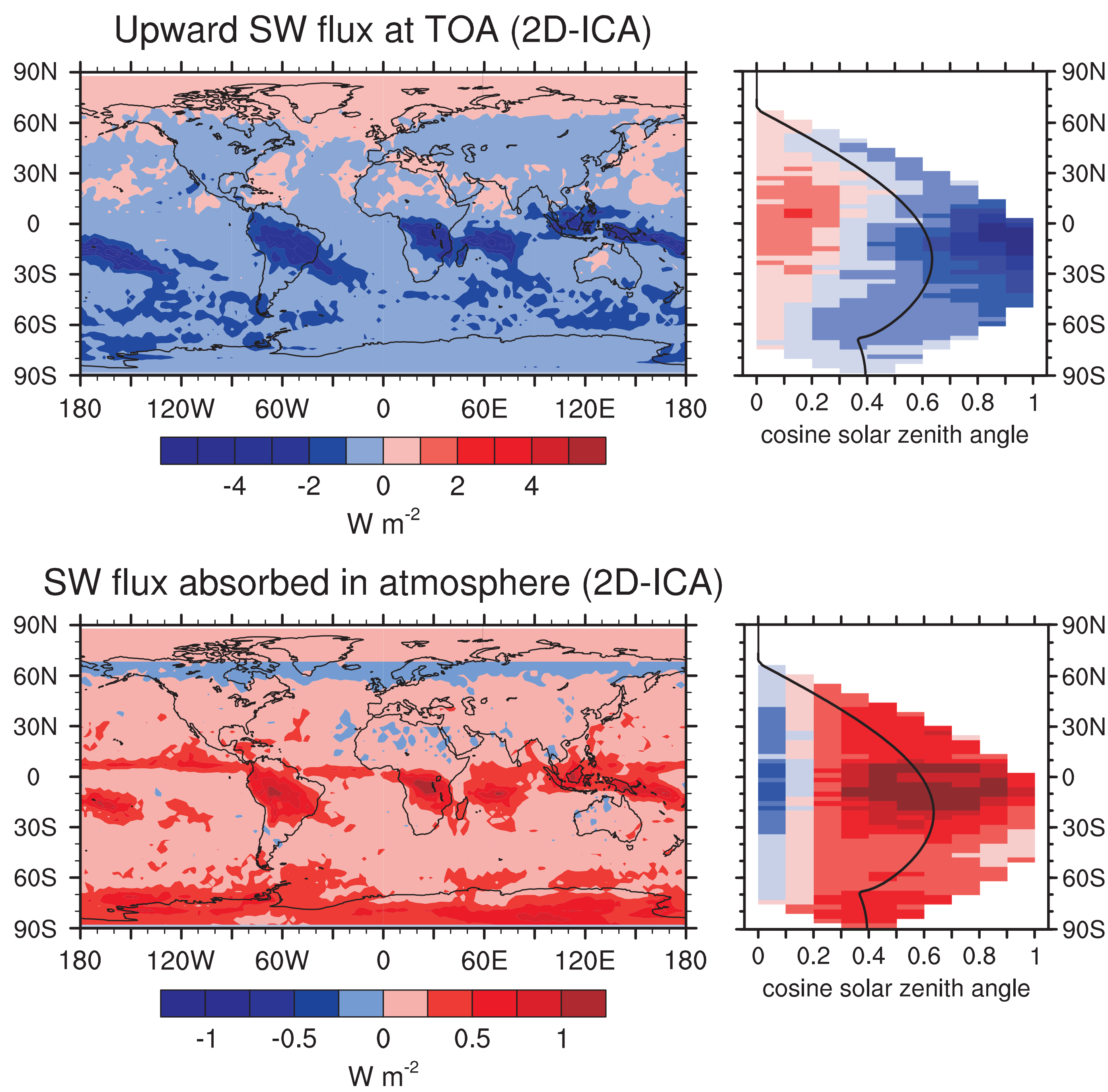
  - $x = 4$ km

  - every 9 hrs for Dec. 2000

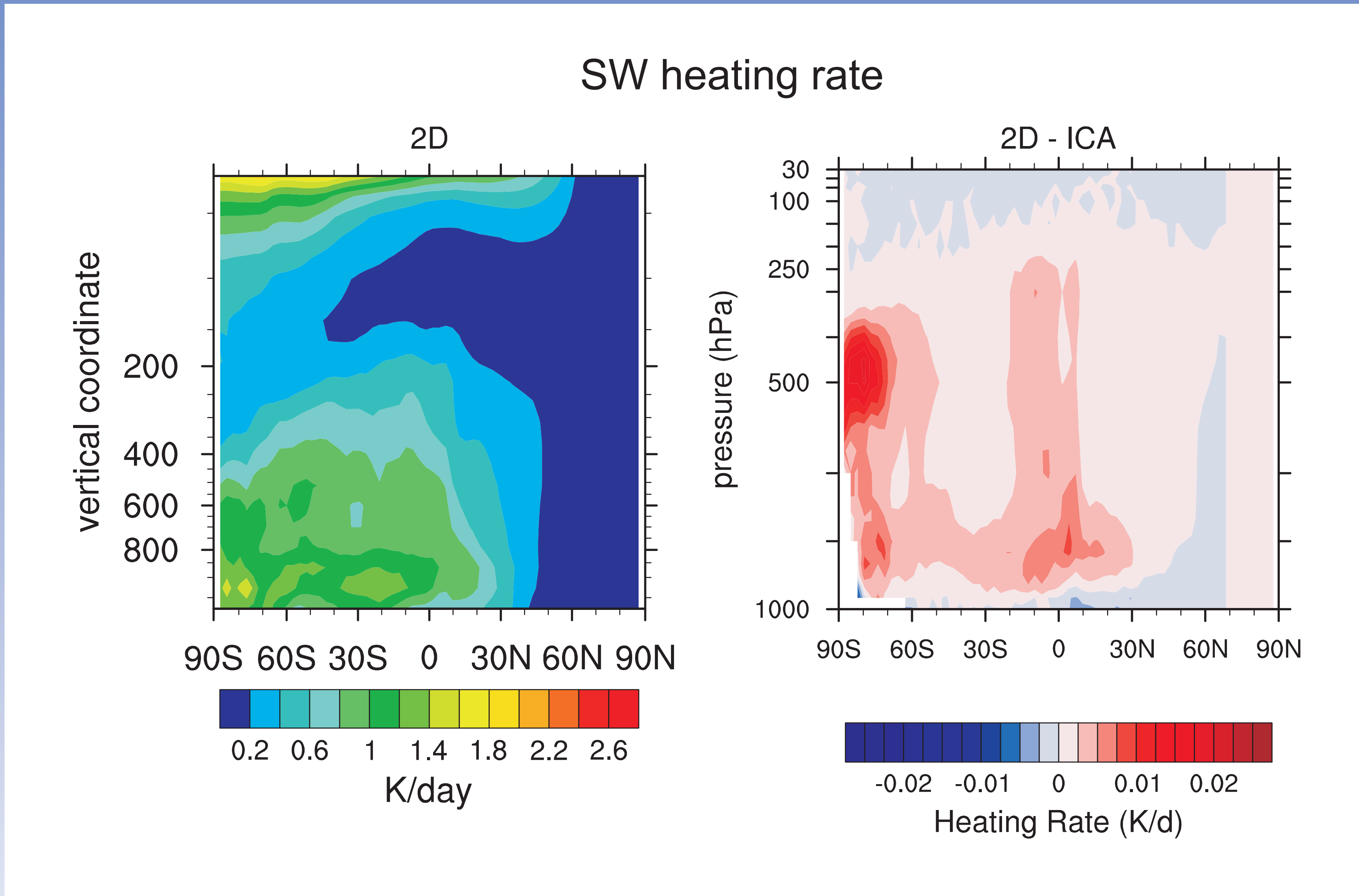
  - 3D MC for SW and LW:

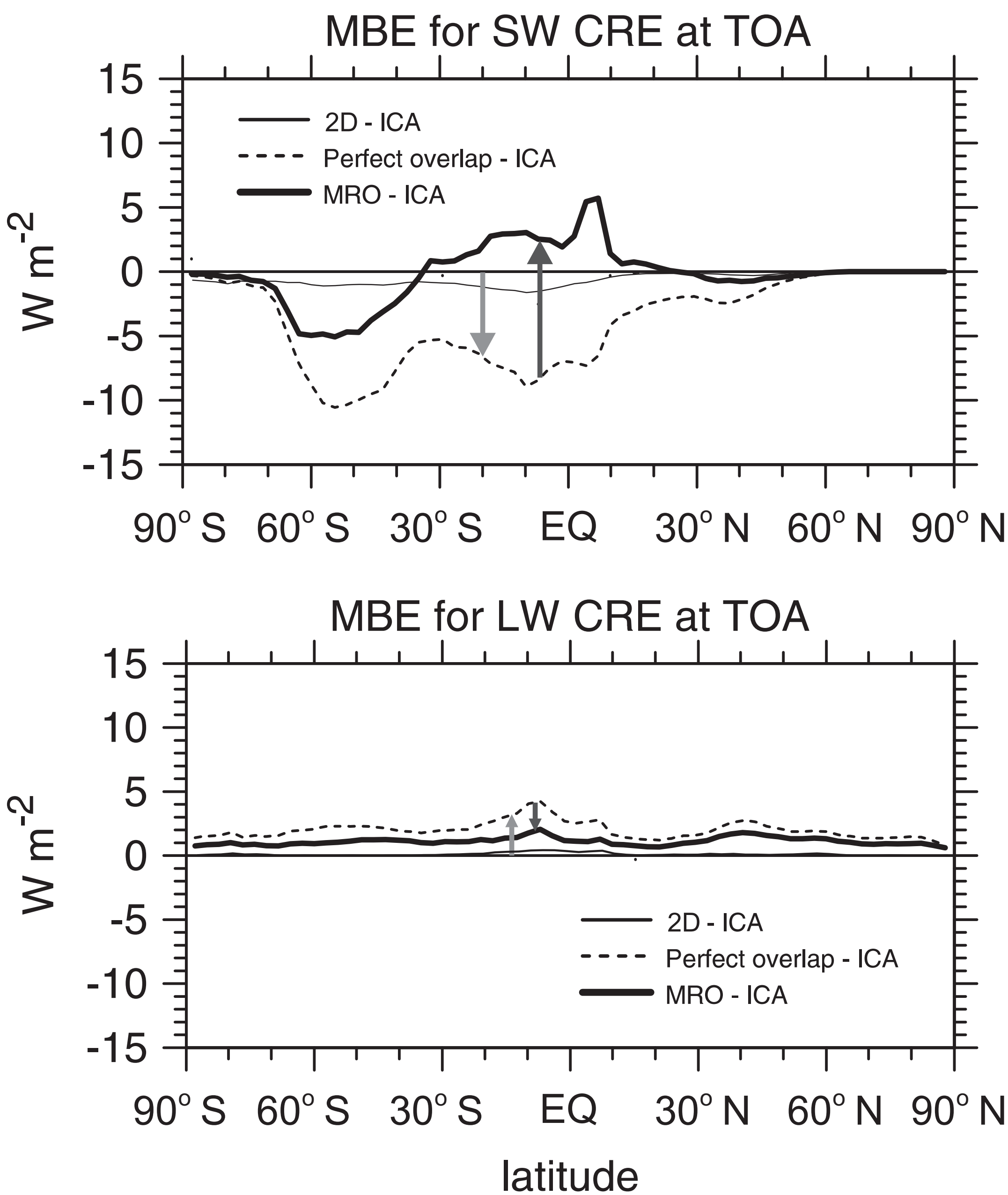
    - Sun incident parallel to CSRM fields

    - domain average profiles: 10^6 photons/field

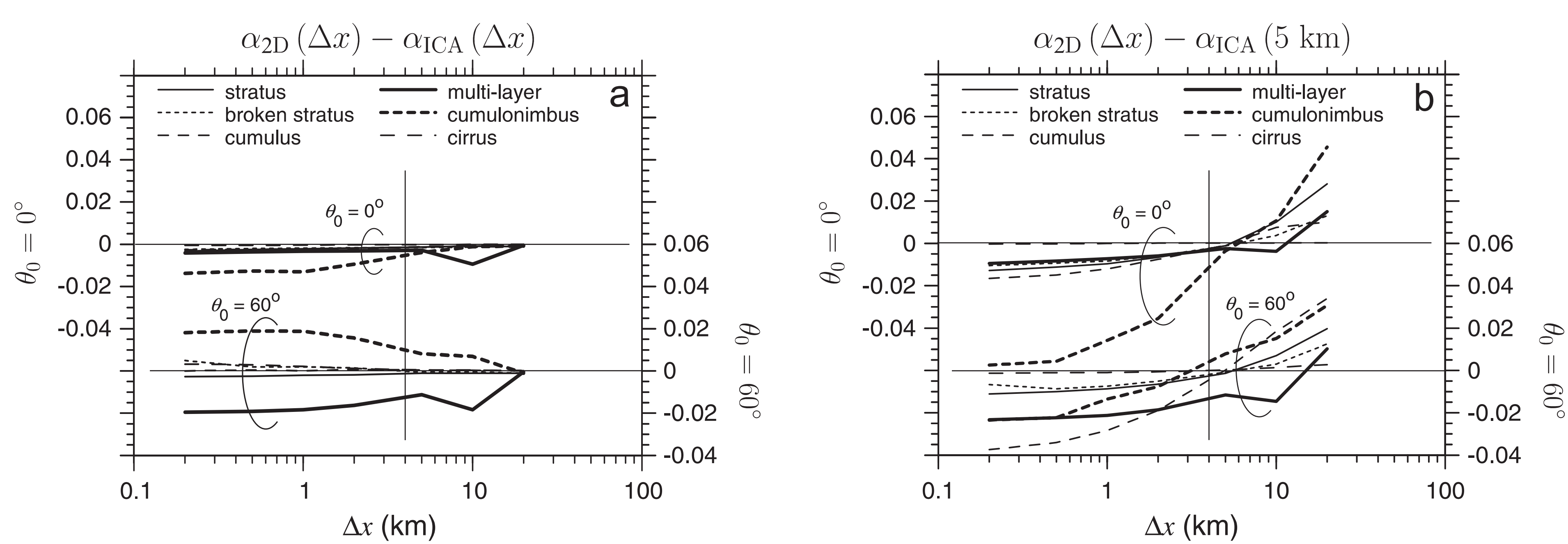


Upward SW flux at TOA (2D-ICA)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-4
-2
0
2
4
W m-2
0
0.2
0.4
0.6
0.8
1
cosine solar zenith angle
SW flux absorbed in atmosphere (2D-ICA)
-1
-0.5
0
0.5
1
W m-2
cosine solar zenith angle


SW heating rate
2D
vertical coordinate
200
400
600
800
90S 60S 30S 0 30N 60N 90N
0.2 0.6 1 1.4 1.8 2.2 2.6
K/day
2D - ICA
pressure (hPa)
30
100
250
500
1000
90S 60S 30S 0 30N 60N 90N
-0.02 -0.01 0 0.01 0.02
Heating Rate (K/d)


MBE for SW CRE at TOA
2D - ICA
Perfect overlap - ICA
MRO - ICA
W m-2
15
10
5
0
-5
-10
-15
90° S
60° S
30° S
EQ
30° N
60° N
90° N
MBE for LW CRE at TOA
2D - ICA
Perfect overlap - ICA
MRO - ICA
W m-2
latitude

How important are 3D effects at x < 4 km?



$$\frac{\partial \alpha_{2D}}{\partial \Delta x} \approx \frac{\partial \alpha_{ICA}}{\partial \Delta x}$$

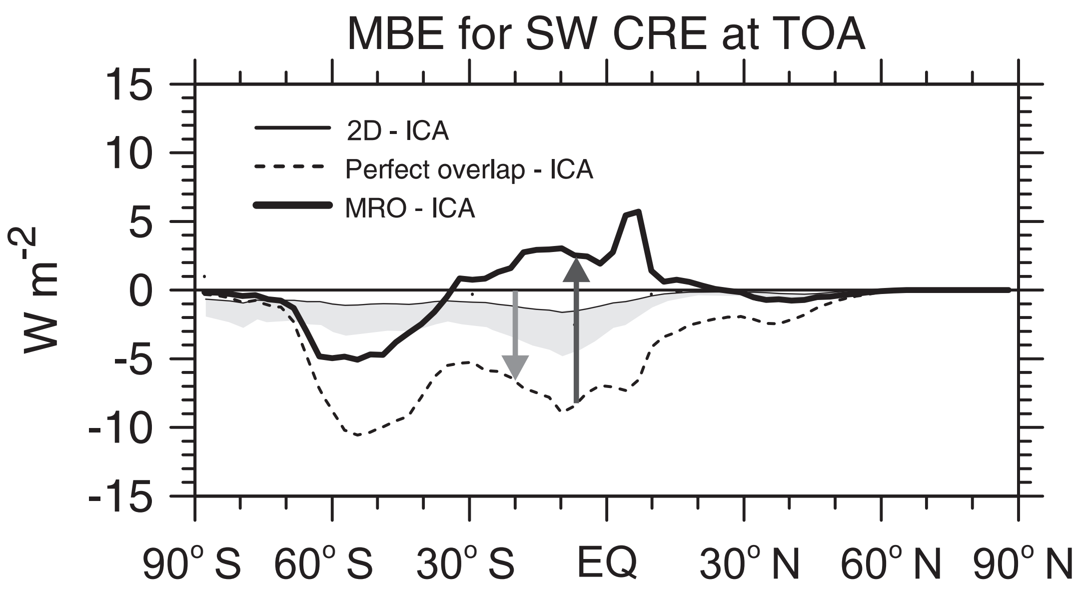
for small x:

$$\frac{\partial \alpha_{2D}}{\partial \text{geometry}} \frac{\partial \text{geometry}}{\partial \Delta x} \approx 0$$

$$\frac{\partial \alpha_{ICA}}{\partial \Delta x} = \sum_{n=1}^{\infty} \frac{\partial \alpha_{ICA}}{\partial \langle \tau^n \rangle} \frac{\partial \langle \tau^n \rangle}{\partial \Delta x}$$

$$\frac{\partial \alpha_{2D}}{\partial \Delta x} = \sum_{n=1}^{\infty} \frac{\partial \alpha_{2D}}{\partial \langle \tau^n \rangle} \frac{\partial \langle \tau^n \rangle}{\partial \Delta x} + \frac{\partial \alpha_{2D}}{\partial \text{geometry}} \frac{\partial \text{geometry}}{\partial \Delta x}$$

$$\left| \frac{\partial \alpha_{ICA}}{\partial \langle \tau^n \rangle} \right| \gtrsim \left| \frac{\partial \alpha_{2D}}{\partial \langle \tau^n \rangle} \right| \to 0$$


MBE for SW CRE at TOA
2D - ICA
Perfect overlap - ICA
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W m^{-2}
15
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90° S
60° S
30° S
EQ
30° N
60° N
90° N

Some practical issues regarding 3D RT and climate modelling

conventional

- Is it worth the effort of accounting for 3D effects in GCMs?

  - E(McICA) = E(ICA) (+ controllable conditional ran. err.)

  - stochastic methods: feasible? how 3D are they?

    - E(stochastic) $\neq$ E(3D) (+ uncontrollable ran. err.)

  - synthetic fields + 3D MC (10^6): feasible | justifiable?

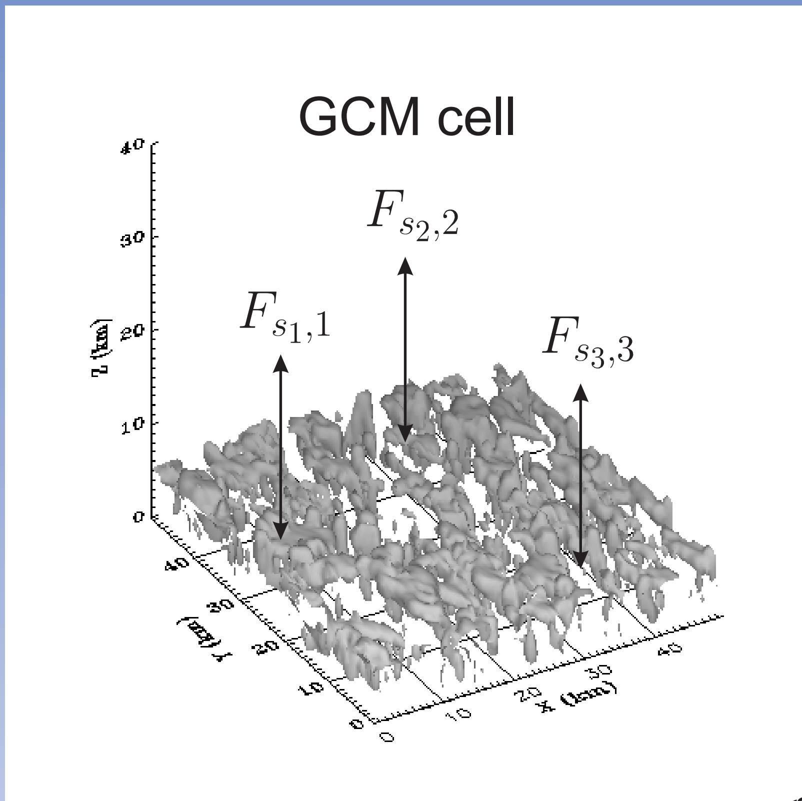
  Has anything been gained?

- 3D MC (10^6) in MMF?

  - good for domain averages, but... Cole et al. (2005)

  How much has been gained?

The Monte Carlo Independent Column Approximation: A Stopgap Solution?



Independent Column Approximation:

$$\langle F \rangle = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} F_n \quad + \quad \mathcal{F}_n = \sum_{k=1}^{\mathcal{K}} F_{n,k}$$

$\boxed{\text{ICA}}$ $\boxed{\text{CKD}}$

$$\langle \mathcal{F} \rangle = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \sum_{k=1}^{\mathcal{K}} F_{n,k}$$

$\boxed{\text{BB - ICA}}$

stochastic generation of unresolved cloud

$$\langle \mathcal{F} \rangle' = \sum_{k=1}^{\mathcal{K}} F_{s_k,k}$$

$\boxed{\text{McICA}}$

a complete separation of optical characteristics from the RT solver!

$$\mathrm{E}(\langle \mathcal{F} \rangle') = \langle \mathcal{F} \rangle = \int \langle \mathcal{F} \rangle' p(\langle \mathcal{F} \rangle')\, d\langle \mathcal{F} \rangle'$$

$$\sigma^2 \geq 0$$

☠ ☠ ☠

? ? ?

$\sigma^2 \geq 0$ ☠ ☠ ☠

? ? ?

- funded by Atmospheric Radiation Measurement (ARM) Programme

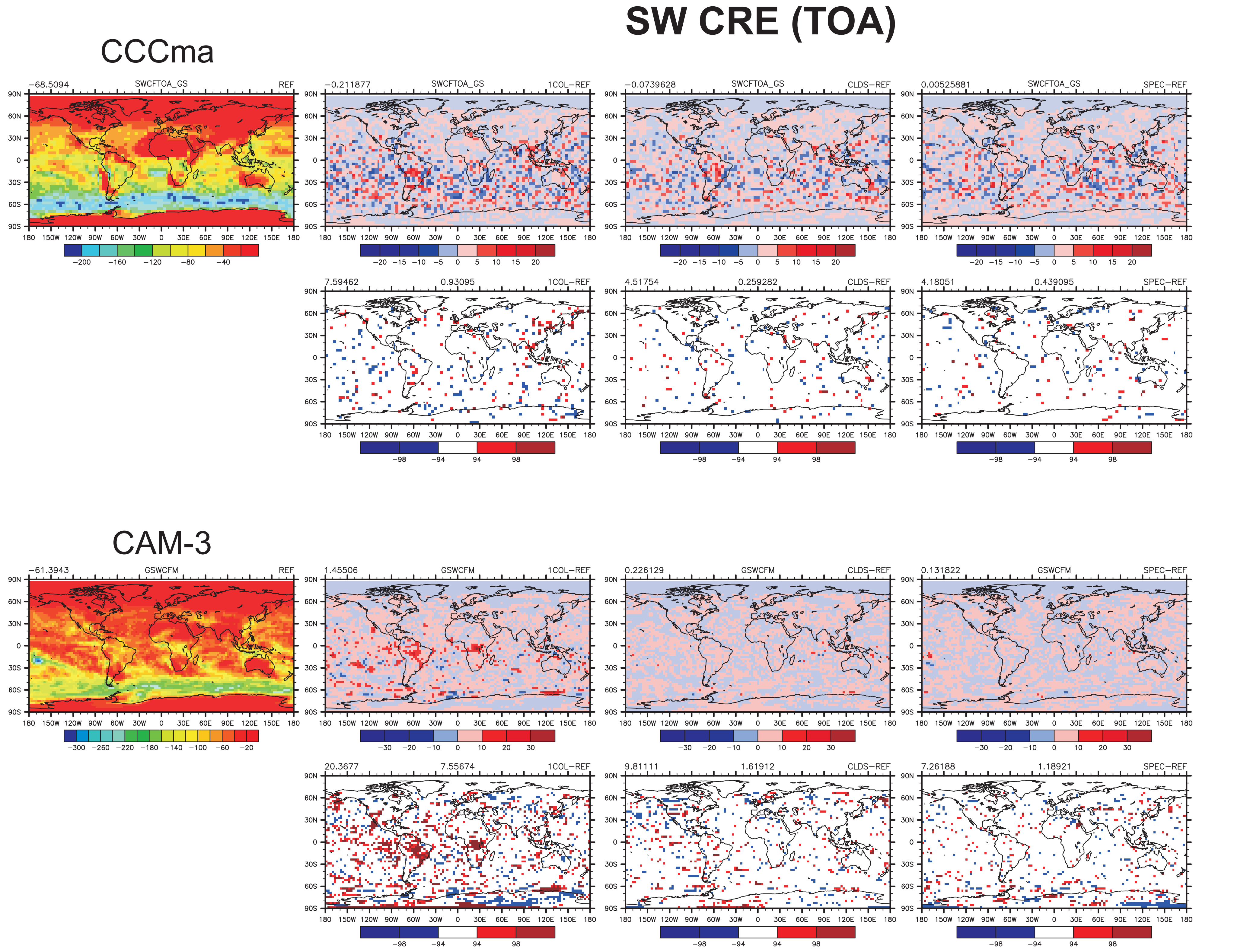
  - fixed SSTs and sea ice

  - 15 day simulations ; 10-member ensembles

  - divergence(noise)

  - ~5 GCMs: CCC, GFDL, NCAR, ECMWF, ECHAM, (GEM, CSU)

  - ultimately multi-year with interactive ocean



SW CRE (TOA)
CCCma
-68.5094 SWCFTOA_GS REF
-0.211877 SWCFTOA_GS 1COL-REF
-0.0739628 SWCFTOA_GS CLDS-REF
0.00525881 SWCFTOA_GS SPEC-REF
7.59462 0.93095 1COL-REF
4.51754 0.259282 CLDS-REF
4.18051 0.439095 SPEC-REF
CAM-3
-61.3943 GSWCFM REF
1.45506 GSWCFM 1COL-REF
0.226129 GSWCFM CLDS-REF
0.131822 GSWCFM SPEC-REF
20.3677 7.55674 1COL-REF
9.81111 1.61912 CLDS-REF
7.26188 1.18921 SPEC-REF

Extending the McICA Method

- cloud microphysics:

  - ice crystal habit and size distribution

  - un(un)resolved variability:

    - x for ICA... Cairns et al.; Petty ; Marshak et al.

- lower boundary condition:

  - distribution of surface types (albedo, emissivity)

Multi-layer canopy as extension of the atmosphere

two-stream solution

Equations for atmospheres and clouds

$$+ \pi F \omega_0 (1 - \beta_0) e^{-\tau/\mu_0}. \quad (11)$$

Two-stream methods are defined for present purposes as methods satisfying the simplified expressions

$$\frac{dI^+}{d\tau} = \gamma_1 I^+ - \gamma_2 I^- - \pi F \omega_0 \gamma_3 e^{-\tau/\mu_0}, \quad (12)$$

$$\frac{dI^-}{d\tau} = \gamma_2 I^+ - \gamma_1 I^- + \pi F \omega_0 \gamma_4 e^{-\tau/\mu_0}, \quad (13)$$

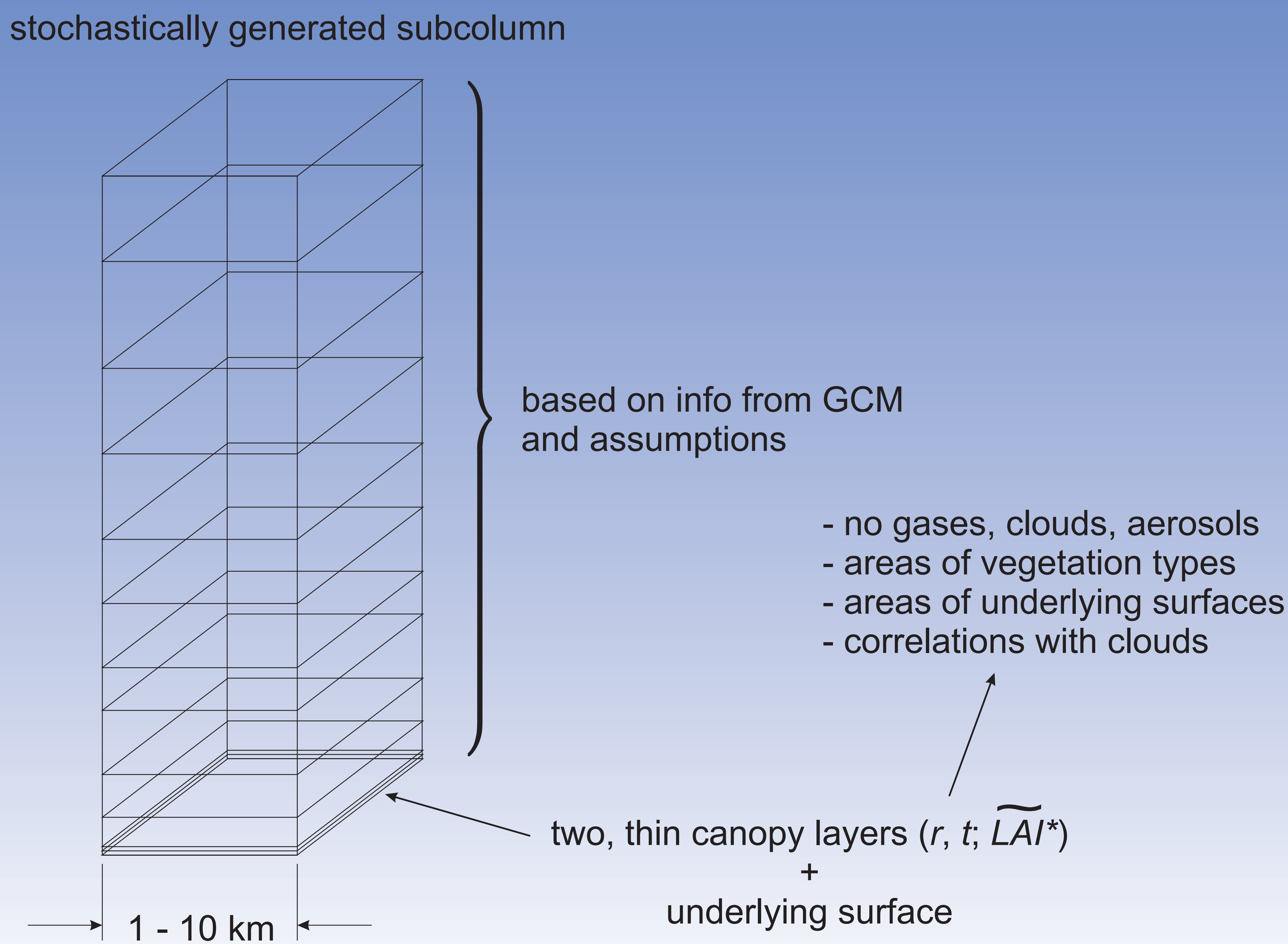
which are obtained from Eqs. (10) and (11) by assuming the μ dependence of I and approximating the integrals. The γ_i's are determined by the approximations used and are independent of τ in all cases. As will be shown, their values are constrained by physical requirements; for example, the constraint $\gamma_3 + \gamma_4 = 1$ follows immediately from energy conservation.

Equations for vegetation

$$\frac{dI^+}{d(\widehat{LAI'}/2)} = \gamma_1 I^+ - \gamma_2 I^- - \pi F \gamma_3 \omega_l \exp(-\widehat{LAI'}/2\mu_0)$$

$$\frac{dI^-}{d(\widehat{LAI'}/2)} = \gamma_2 I^+ - \gamma_1 I^- + \pi F \gamma_4 \omega_l \exp(-\widehat{LAI'}/2\mu_0)$$

B. Pinty, GRC 2005


stochastically generated subcolumn
based on info from GCM
and assumptions
- no gases, clouds, aerosols
- areas of vegetation types
- areas of underlying surfaces
- correlations with clouds
two, thin canopy layers (r, t; $\widetilde{LAI}^*$)
+
underlying surface
1 - 10 km

Summary

- worth worrying about 3D (vs. ICA)?
- parametrize 3D RT in GCMs before MMF makes it explicit?
- McICA noise experiments
- extensions to surface, ice habits, etc...